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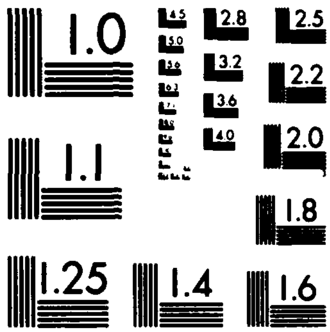

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AFGL-TR-87-0112

Balloon Track Data Analysis

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31 March 1987

Final Report
3 July 1985-31 March 1987

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This report summarizes the step activities that were performed in the Balloon Track Data Analysis for AFGL/LWG.

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1. INTRODUCTION

1.1 Background

The Air Force Geophysics Laboratory (AFGL) is developing a program to verify gravity models by directly measuring gravity using high-altitude balloons. Gravity is measured using a very accurate vibrating string accelerometer (VSA) gravimeter as part of a balloon gondola package.

Although the gravimeter package senses the acceleration due to gravity, it also senses accelerations due to motion of the gondola package. These accelerations consist of translational accelerations of the gondola package as well as accelerations due to rotational motion of the gondola package, i.e., pendulum effects and rotations of the gondola package about its own axis.

The pendular motion of the gondola package also perturbs the gravity measurements in another way, in that the deflection of the gondola package from the local vertical (the direction of the gravity vector) causes errors in the estimate of gravity at that point, since the gravimeter axis is no longer aligned with the local vertical.

Another important consideration in using this technique to estimate gravity is that accurate knowledge of the gravimeter's position is necessary in order to compare measured results with gravity models at the gravimeter location.

Given that the actual acceleration, deflection, horizontal velocity and position errors are orders of magnitude larger than the limits shown, using unprocessed gravimeter data as the gravity estimate would be completely unsatisfactory. The solution proposed by AFGL involves the accurate determination of the motion of the gondola package (position, velocity, acceleration, and rotation) and use of this information to correct the gravimeter's measurement. The combination of an accurate tracking system and an inertial motion sensing package (IMSP) is required in order to estimate gondola position, velocity, and acceleration accurately.

In October 1983, a launch of a high-altitude balloon was conducted by AFGL personnel at Holloman AFB in New Mexico. The balloon gondola package included a VSA gravimeter and an inertial motion sensing package which included 3 orthogonal accelerometers, 3 orthogonal rate gyros, and 3 orthogonal magnetometers. Gondola position tracking was done by three ground-based digital radars located at White Sands Missile Range (WSMR).

The objectives of this flight were to demonstrate the feasibility of measuring gravity using a high-altitude balloon and to evaluate the performance of the digital radar in tracking the balloon. It was not to estimate gravity to 1 mgal accuracy, although it was hoped that the data could be processed in some way to improve the raw gravimeter output.

The launch was a success in that all balloon-based instrumentation worked properly and the telemetry link worked smoothly; thus, the soundness of AFGL's program was demonstrated. However, the accuracy of the digital radar was not sufficient to meet the needs of the program. WSMR provided 46 tapes of balloon-tracking data which included balloon position and velocity estimates and their errors. Errors as reported by WSMR are on the order of 2-4 m in position, 1.5 m/sec in velocity and 1 m/sec^2 in acceleration. Comparing these numbers with the required accuracy to yield gravity errors of 1 mgal (3m, 0.05 m/sec, 10^{-5} m/sec^2), one can see that the digital radar provided by WSMR is not accurate enough for the needs of the program. Compounding these inadequacies, subsequent analysis of the radar position estimates by AFGL and BEDFORD RESEARCH personnel indicate that the 2-4 meter position errors reported by WSMR are overly optimistic.

One of the strongest conclusions from the results of the October 1983 flight is that an improved method of tracking is required for subsequent flights. It is believed that the use of the NAVSTAR Global Positioning System (GPS) may provide position, velocity, and acceleration estimates which are accurate enough to achieve a 1 mgal accuracy in estimating gravity.

1.2 Objectives

The primary goal of this program was to design a post-flight data processing system to measure gravity to 1 mgal accuracy. The purpose was to analyze data from balloon flights and to assess the feasibility of measuring gravity to this accuracy. Emphasis during the effort would be on determining the relative contribution of the various error sources to the overall error budget.(1 mgal).

Primary emphasis was on assessing the performance of GPS as the main tracking system. To facilitate this assessment, a direct comparison of the accuracies in determining gondola position, velocity, and acceleration will be made between GPS tracking, radar tracking, and combined tracking performance. It is anticipated that using a differential-GPS approach would yield position, velocity, and acceleration accuracies which are significantly better than ground-based radar.

The proposed method of estimating gravity based on gravimeter, gondola package tracking data, and inertial motion sensing package data involves an integrated high-order Kalman filter approach. The problem at hand is well suited to this type of approach since the observations (gravity, tracking, and inertial motion sensing package data) can be optimally combined and expressed as a function of states which are to be estimated (position, velocity, and acceleration, gondola attitude, etc.).

The use of a high-order Kalman filter approach has many advantages:

1) The theory and applications are well understood and established through years of use.

2) A unified and theoretically sound approach is provided for using measurements from different sources and of different accuracies.

3) The approach is general enough so that performance comparisons like determining position, velocity, and acceleration accuracy can be made by using different sets of observations such as GPS information or radar tracking, etc.

4) The contribution of individual error sources can be estimated and identified, and thus lead to the determination of an appropriate error budget.

5) Corrected gravimeter measurements (the gravity estimate) is a standard output of the filter mechanism.

6) The approach leads to reduced software complexity over multi-stage implementation.

There are several approaches to the development of the post-processing software algorithms. One approach treats the GPS and/or radar systems as primarily tracking sensors that provide accurate information on the position, velocity, and acceleration of the gondola package (particularly the gravimeter). These estimates can be corrected for local perturbations in acceleration and rotation using the IMSP sensor package. This approach, while sound in concept and simple in application, assumes a major responsibility on the tracking systems to satisfy the accuracy requirements of the program. Field testing of GPS receivers has shown that even in benign operating environments, stand-alone set performance has not been able to achieve the accuracies stipulated in this program. Studies have shown that use of differential GPS techniques can significantly improve performance (providing close to the 3-meter accuracy requirement stipulated in the RFP). However, velocity and acceleration accuracies are not significantly changed from absolute GPS performance, and are not sufficient to satisfy the requirements of the gravity measurement experiment. (Typical velocity accuracies are of the order of 0.2 and 0.5 m/sec.) Furthermore, when combined with accelerometer and gyro data from an unaided IMSP, errors will tend to grow with time and pose a serious overall performance degradation over the anticipated trajectory for the balloon flight.

In order to use the information available from the gondola and ground sensor systems to the maximum extent, a more sophisticated approach is proposed for this effort. A Kalman filter estimating the primary error sources in a strapdown inertial system was designed, utilizing the IMSP as the reference strapdown inertial system, with GPS and radar providing measurements to the reference system. These measurements are differenced with predicted measurements in a classical inertial error filter mechanization. An error state formulation is advocated because of the numerical stability it affords.

The optimal error estimates that are outputs of the filter processing are combined with whole value outputs from the accelerometers and gyros to provide best estimates of gondola position, velocity, acceleration, and attitude. By utilizing the gravimeter as the primary vertical accelerometer on the gondola, the estimates of gravity are output as a standard output from the filter package.

Three separate areas of error are inherent in this gravity experiment. They are:

1) Balloon Trajectory Estimation Errors: These errors relate to the uncertainty in absolute position, velocity, and acceleration of the gondola. Absolute estimates are obtained by combining reference system outputs with errors estimated in the filtering process.

2) Gondola Orientation Estimation Errors: These errors arise from local perturbations in gondola orientation and acceleration (pendulosity, gondola rotation). Estimates of gondola attitude derived from the Kalman filter provide the information necessary to determine the attitude relative to a reference coordinate system.

3) Gravimeter Sensor Errors: These errors arise from instrument errors such as calibration, misalignments, and biases in the gravimeter itself.

Each of these error sources contributes to the overall error budget that will ultimately determine the accuracy to which gravity can be measured. The gravimeter itself is a highly accurate instrument, and its errors do not play a large role in limiting overall measurement accuracy. The major contribution to the error results from the coupling of gravimeter measurements to less accurate IMSP, GPS, and radar measurements. This coupling results from non-smooth gravimeter motion introducing attitude, velocity, and radial acceleration errors that have to be resolved along the local vertical.

In order to fulfill the stringent performance requirements of the proposed gravity measurement experiment utilizing GPS, radar, and IMSP sensors, the offeror developed a unified set of computer programs for post-processing of the flight-recorded data. At the heart of this post-processor software is the high-order Kalman filter. Incorporated in this Kalman filter are error models for a strapdown mechanization of the IMSP sensor inertial package. This Kalman filter is designed to use the available flight data selectively to yield refined gondola trajectory (position, velocity, and acceleration) and attitude estimates, and to analyze the contributions of individual sensors to the accuracies obtainable through the filtering process.

1.3 Report Organization

The subsequent sections of this report are dedicated to describing the software system that was developed to perform the post-processing of the AFGL High-Altitude Balloon Data. It provides a summary of the entire system with an emphasis on the architecture and content of the Kalman filter software. Sections 2 through 5 are arranged as follows:

Section 2: A discussion of the standards used for designing, programming, testing and implementing the software system.

Section 3: A functional description of the methods and procedures used in the software development phase.

Section 4: Example of a filter run.

2. STANDARDS AND CONVENTIONS

This section describes the programming languages used to develop this system. In addition, the methods for programming and documenting the software are included.

2.1 Programming Standards

The primary languages used in the development of this system were FORTRAN and I*S*P (Interactive Signal Processor). The goals of the software coding were correctness and maintainability. Correctness is defined as the degree to which the program satisfies the specifications, while maintainability refers to the ease of modification.

2.2 Specification Standards

A top-down approach was used in designing and coding the programs within the system (Demarco, 1979). This technique starts with a high-level diagram of the system and then decomposes it into major processes and data flow. These processes are further decomposed into a sequential set of modules.

Internal software documentation was performed according to the following guidelines:

- A prologue was included at the beginning of each program to explain the basic function of each module.
- A header was written at the top of each module to describe its purpose and reference supporting documentation (e.g., functional specifications) to substantiate data flow or mathematical operations.

Scientific Report No. 1 on this contract contains a detailed description of the filter specifications.

2.3 Test and Verification Methods

The software developed for this system was subjected to a variety of internal and external validation procedures. The objective was not only to verify the accuracy and completeness of all computer programs but also to ensure that all required operations had been adequately addressed.

The internal testing procedures entailed cross-checking each algorithm with available documentation (e.g., functional specifications) to ensure that the proper operations were being performed. In addition, the NAMES and UNITS assigned to each variable were examined independently, and in the context of all algorithms, to correct any improper or redundant usage.

External testing procedures involved executing the programs on simulated or real data sets. Simulated data was generated to model the balloon motion, on-board sensors, and ground station receivers that were used in the filter. Since there is no reference system available for the balloon flight that is more accurate than the GPS measurement, the prime system under investigation, the need for a validation tool is critical to the filter software. With a simulator, errors in the sensors, gravity, and GPS range biases can be introduced as known quantities and their values estimated by the filter. The actual estimation of known errors by the filter is validation that the proper operations are being performed by the filter. Filter tuning, such as adjustments of process noise and measurement noise terms, are part of this process and are based on expected sensor performance obtained from the simulator. Thus, the Kalman filter software can be tested and tuned for accuracy, stability, and convergence by the simulator software.

3. SYSTEM OVERVIEW

This section describes the purpose of the software system by reviewing the functions that are performed. It further identifies the system requirements and demonstrates how they were satisfied.

3.1 Application

This system processes data from several different sources in an effort to provide estimates for the balloon gondola position, velocity, and acceleration. To achieve this goal, four different functions were identified and referenced as Investigator Tape Creation, Analysis File Preparation, Differential GPS Bias Filter, and Navigation Error Filter functions, respectively. The Investigator Tape Creation function involves the reduction of a large volume of raw experimental data to a format that incorporates and multiplexes the relevant channels of flight data in an orderly manner. The Analysis File Preparation function selects and merges a user-defined interval of data from the Investigator Tape with the GPS exchange tape to provide a unified data file. The Differential GPS Bias Filter processes ground station data to determine the differential GPS corrections. The Navigation Error Filter function determines the gondola package motion.

3.2 Requirements

The software requirements for each major operation are presented in this section. These requirements were established from meetings with AFGL personnel and supporting documentation (e.g., Functional Specifications).

3.2.1 Investigator Tape Requirements

The requirements for the Investigator Tape creation function were as follows:

- All data streams must be converted from 8 to 16 bit words and calibrated accordingly. (See Figure 3-1 for calibration numbers.)

j	MEASUREMENT	SCALE FACTOR	OFFSET
1	VSA		
2	OVEN TEMP.	10.0 DEG C/VOLT	20.0 DEG C
3	MAGNETIC COMPASS	5 VOLTS/360 DEGREES	
4	BOX TEMP.	10.0 " " "	20.0 " "
5	X GYRO (LOW)	0.4225 DEG/SEC/VOLT	-1.095 DEG/SEC
6	Y GYRO (LOW)	0.4464 " " "	-1.126 DEG/SEC
7	Z GYRO (LOW)	-.4375 " " "	1.103 " "
8	X GYRO (HIGH)	.04367 " " "	-.1443 " "
9	Y GYRO (HIGH)	.04464 " " "	-.1143 " "
10	Z GYRO (HIGH)	-.08997 " " "	.2352 " "
11	X ACCL (LOW)	-1.948 M/SEC**2/VOLT	4.882 M/SEC**2
12	Y ACCL (LOW)	-1.954 " " "	4.893 " "
13	Z ACCL (LOW)	1.995 " " "	4.918 " "
14	X ACCL (HIGH)	-.07787 " " "	.1954 " "
15	Y ACCL (HIGH)	-.07815 " " "	.1999 " "
16	Z ACCL (HIGH)	.07838 " " "	9.608 " "
17	X MAG.	-238.9 MILLIGAUS/VOLT	-597.8 MILLIGAUS
18	Y MAG.	-239.7 " "	-599.3 "
19	Z Mag.	239.2 " "	-598.5 "

FIGURE 3-1: AFGL Gravity Package Calibration Numbers

The balloon-flight IMSP data must be converted from scientific units to engineering units before being used in any calculations. The data is converted according to the relation:

ENGINEERING DATA (J) = SCIENTIFIC DATA (J)*(5/4095)*SCALE(J) + OFFSET(J)

Magnetic compass data is converted by the relation:

ENGINEERING DATA (J, WHERE J=3) = SCIDATA(J)*(5/360)*SCALE(J) + OFFSET(J)

A list of scale factors and offsets are found in Figure 3-1. In addition to the above conversions, the time is converted from ZULU to GPS.

TTAG = TTAG + 345600.

- Values resulting from transmission, recording, or instrumental errors must be identified and recoded. Recoding will be through either interpolation or default parameters (-999).

- Overlapping time segments that represent redundant information will be deleted.

- The data will be time sequenced at a sampling rate of .1 seconds.

- The data values in the file will conform to the specifications presented in Figure 3-2.

3.2.2 Analysis File Requirements

The analysis files integrate ephemeris clock, pseudorange, doppler, and VSA measurements into one file. This function was designed to minimize the amount of I/O operations and resources (e.g., tape drives) required during filtering.

The requirements for the Analysis File functions are as follows:

- It must provide the user-interface the ability to select discrete time intervals and give user feedback during the course of programming.

- It must include diagnostic messages that will inform the user when error conditions occur and the probable cause of these errors.

- It must extract the records from each of the designated files, begin at the starting point, and merge and sort them. This sort will use the time tag as the major key and the record type (Block #) as the minor key.

- It will create and write an ouput file in a format that is specified by the filter.

DATA VALUES DESCRIPTION OF INVESTIGATOR VERSION 1 DUCKYII

ITEM #	DESCRIPTION	UNITS	FORMAT	DEFAULT
1	TIME	ZULU SECONDS	F10.3	-99.
2	RADAR X	METERS	F10.2	-99.
3	RADAR Y	METERS	F10.2	-99.
4	RADAR Z	METERS	F10.2	-99.
5	RADAR SIGMA X	METERS	F10.2	-99.
6	RADAR SIGMA Y	METERS	F10.2	-99.
7	RADAR SIGMA Z	METERS	F10.2	-99.
8	COMPUTED GEOCENTRIC X	METERS	F11.2	-99.
9	COMPUTED GEOCENTRIC Y	METERS	F11.2	-99.
10	COMPUTED GEOCENTRIC Z	METERS	F11.2	-99.
11	COMPUTED GEOCENTRIC SIGMA X	METERS	F8.2	-99.
12	COMPUTED GEOCENTRIC SIGMA Y	METERS	F8.2	-99.
13	COMPUTED GEOCENTRIC SIGMA Z	METERS	F8.2	-99.
14	COMPUTED GEODETIC X	DEGREES	F12.7	-99.
15	COMPUTED GEODETIC Y	DEGREES	F11.7	-99.
16	COMPUTED GEODETIC Z	METERS	F10.2	-99.
17	COMPUTED GEODETIC SIGMA X	METERS	F10.2	-99.
18	COMPUTED GEODETIC SIGMA Y	METERS	F10.2	-99.
19	COMPUTED GEODETIC SIGMA Z	METERS	F10.2	-99.
20	RADAR GEODETIC X	DEGREES	F10.2	-99.
21	RADAR GEODETIC Y	DEGREES	F11.7	-99.
22	RADAR GEODETIC Z	METERS	F12.2	-99.
23	VSA RAW DATA	COUNTS	I10	-9999999
24	INNER OVEN VOLTAGE	INTEGER	I8	-9999999
25	OUTER OVEN VOLTAGE	INTEGER	I8	-9999999
26	MAGNETIC COMPASS HEADING	INTEGER	I8	-9999999
27	MOTION SENSOR BOX TEMPERATURE	INTEGER	I8	-9999999
28	X GYRO - LOW GAIN	INTEGER	I8	-9999999
29	Y GYRO - LOW GAIN	INTEGER	I8	-9999999
30	Z GYRO - LOW GAIN	INTEGER	I8	-9999999
31	X GYRO - HIGH GAIN	INTEGER	I8	-9999999
32	Y GYRO - HIGH GAIN	INTEGER	I8	-9999999
33	Z GYRO - HIGH GAIN	INTEGER	I8	-9999999
34	X ACCELEROMETER - LOW GAIN	INTEGER	I8	-9999999
35	Y ACCELEROMETER - LOW GAIN	INTEGER	I8	-9999999
36	Z ACCELEROMETER - LOW GAIN	INTEGER	I8	-9999999
37	X ACCELEROMETER - HIGH GAIN	INTEGER	I8	-9999999
38	Y ACCELEROMETER - HIGH GAIN	INTEGER	I8	-9999999
39	Z ACCELEROMETER - HIGH GAIN	INTEGER	I8	-9999999
40	X MAGNETOMETER	INTEGER	I8	-9999999
41	Y MAGNETOMETER	INTEGER	I8	-9999999
42	Z MAGNETOMETER	INTEGER	I8	-9999999
43	PRESSURE ALTIMETER (0-15 PSI)	INTEGER	I8	-9999999
44	PRESSURE ALTIMETER (0-2 PSI)	INTEGER	I8	-9999999
45	PRESSURE ALTIMETER (0-0.5 PSI)	INTEGER	I8	-9999999
46	COMMAND VERIFICATION MONITOR	INTEGER	I8	-9999999
47	FLIGHT TERMINATION MONITOR	INTEGER	I8	-9999999
48	VSA POWER CONVERTER TEMPERATURE	INTEGER	I8	-9999999
49	Z80 CARD CAGE TEMPERATURE	INTEGER	I8	-9999999

FIGURE 3-2

50	GPS #1 TEMPERATURE	INTEGER	I8	-9999999
51	GPS #2 TEMPERATURE	INTEGER	I8	-9999999
52	DIGIDATA TAPE UNIT TEMPERATURE	INTEGER	I8	-9999999
53	UP CAMERA TEMPERATURE	INTEGER	I8	-9999999
54	DOWN CAMERA TEMPERATURE	INTEGER	I8	-9999999
55	C-BAND XPONDER TEMPERATURE	INTEGER	I8	-9999999
56	DATA XMITER #1 TEMPERATURE	INTEGER	I8	-9999999
57	DATA XMITER #2 TEMPERATURE	INTEGER	I8	-9999999
58	BATTERY SECTION #1 TEMPERATURE	INTEGER	I8	-9999999
59	BATTERY SECTION #2 TEMPERATURE	INTEGER	I8	-9999999
60	VSA 28V MONITOR	INTEGER	I8	-9999999
61	GPS 28V MONITOR	INTEGER	I8	-9999999
62	PRIMARY 28V MONITOR	INTEGER	I8	-9999999
63	BACKUP 28V MONITOR	INTEGER	I8	-9999999
64	PRIMARY 12V MONITOR	INTEGER	I8	-9999999
65	BACKUP 12V MONITOR	INTEGER	I8	-9999999
66	Z80 5V MONITOR	INTEGER	I8	-9999999
67	PRIMARY CMD. RX. SIG. STRENGTH	INTEGER	I8	-9999999
68	BACKUP CMD. RX. SIGNAL STRENGTH	INTEGER	I8	-9999999
69	VSA INNER HEAT BLANKET VOLTAGE	INTEGER	I8	-9999999
70	VSA OUTER HEAT BLANKET VOLTAGE	INTEGER	I8	-9999999
71	DIGITAL MONITOR #1	INTEGER	I8	-9999999
72	DIGITAL MONITOR #2	INTEGER	I8	-9999999
73	DIGITAL MONITOR #3	INTEGER	I8	-9999999
74	DIGITAL MONITOR #4	INTEGER	I8	-9999999
75	DELTA TIME FOR VSA	INTEGER	I10	-9999999
76	SPLINED DELTA TIME FOR VSA	REAL	E14.7	-9999999.
77	COMPUTER GRAVITY	MILLIGALS	F14.7	-9999999.

FIGURE 3-2, cont.

3.2.3 Differential GPS Bias Filter Requirements

The requirements for the differential GPS bias filter function are as presented. It must:

- Process pseudo-range and doppler phase measurements from all GPS ground stations to estimate the differential bias corrections.
- Check the receiver status before using each measurement.
- Check the residual reasonableness of each measurement before it is incorporated.
- Use weather data to make the tropospheric propagation delay correction for each measurement.
- Use dual frequency measurements on L1 and L2 to make ionospheric propagation delay corrections for each measurment.
- Correct time offsets when available.
- Use all new satellite ephemeris data when available.
- Incorporate measurements using a square root filter update algorithm.
- Re-initialize bias states when the tracked satellite constell tion changes.
- Store its filter state estimates of satellite biases and their covariance on a data file.
- Store intermediate data for test and diagnostic purposes.

3.2.4 Navigation Error Filter Requirements

The requirements for the navigation error filter function are as follows. It must:

- Process any subset of the following data sets:
  - Standard GPS data and differential GPS bias data
  - Radar position data only or position and velocity data
  - VSA data
  - Magnetic compass data
- Process each selected data set at the specified skip rate.
- Process pseudorange and doppler phase measurements from the balloon GPS set to estimate the gondola position, velocity and acceleration.
- Use weather data to make the tropospheric propgation delay correction for each measurement.
- Use dual frequency measurements on L1 and L2 to make ionospheric propagation delay corrections for each measurment.
- Correct time offsets when available.
- Use all new satellite ephemeris data when available.
- Check the receiver or sensor status before using each measurement.
- Check the residual reasonableness of each measurement before it is incorporated.
- Use the inertial measurement data (accelerator and gyro data) to propagate the whole value of the gondola motion.
- Incorporate measurements using a square root filter update algorithm.
- Store its filter state estimates and their covariances on a data file.
- Store intermediate data for test and diagnositic purposes.

3.3 Functional Organization

This section describes the overall functional behavior of the software system, the principal modes of operation and the different software configurations.

A flow diagram of the post-flight software system is presented in Figure 3-3. Raw pre-processed data is furnished on several tapes, each of which contains one or more files. These tape files have unique characteristics and are individually examined to identify and correct missing or invalid data items. The modified files are then written to an Investigator Tape that contains a comprehensive data base of all flight recorder and telemetry data. (See Section 3.7 for more details.)

Data from the Investigator and GPS Exchange tapes are then merged, sorted, and formated for use by either the Differential Bias and/or Navigational Filter. The newly merged file is placed on a mass storage disk for reader access. Filtering can then be performed on all or part of a file, depending on the user's specifications.

At this stage, the user may elect to created simulated data to run through the filter. Simulator software was written to enhance the analytical process of fine tuning and externally validating the filter operations. Both real and simulated data have the same file structure and format.

Kalman filtering can then be accomplished by running the Navigation Filter software alone or in conjunction with the Differential GPS Bias routine. As shown in Figure 3, the user must first implement the Bias software before running the Navigation program. The justification for this procedure is that the Navigation Filter uses the output from the Bias software to improve its estimates of the balloon's location. The results are written to mass storage for inspection.

3.4 Software Configurations

A flow chart depicting the software written to fulfill the requirements of this system is presented in Figure 3-3. The actual program names and the sequential method of executing them is provided. Further, these programs are presented in the context of the functions they address.

```
   ---------------------
   |Insert Science Data|
   |    (SCIDATA)      |
   ---------------------
            |
            V
 -------------------------
 |Convert VSA to Gravity|
 |  (VSA_TO_GRAVITY)     |
 -------------------------
            |
            V
    --------------------
    |Insert Radar Data|
    |    (TRACKING)    |
    --------------------
            |
            V
     ( Investigator
          Tape )
            |
            V
 --------------------------
 |Extract Data for Filter|
 |  (DOWN_LOAD_GRAVITY    |
 --------------------------
            |
            V
---------------------------------
|Convert to Engineering Units|
|          (CONVERT)            |
---------------------------------
            |
            V
     ----------------        -------------------------------------
     |Merge with GPS|        |Extract GPS Data for Ground Filter|
     |  (TCSECRF)    |        |             (TCSECT3)             |
     ----------------        -------------------------------------
            |                                 |
            |                                 V
            |                          ----------------
            |                          |Ground Filter|
            |                          ----------------
            |                                 |
            V---------------------------------V
                          |
                          V
                 ---------------------
                 |Navigational Filter|
                 |     (NAVFIL)       |
                 ---------------------
```

FIGURE 3-3: Software Flow Chart

3.4.1 Investigator Tape Software

The first step was to create a uniform Investigator Tape from the IMSP, VSA and radar tracking data. This was accomplished by three FORTRAN programs. The first program read in the Science data, IMSP and raw VSA, verified the time code associated with each segment, and inserted them into an Investigator Tape. During this process, many timing errors, time reversals and unreadable time or data values were found.

The second program needed was a conversion of the raw VSA data into gravity values. This was done by differencing the raw VSA values, applying a multiplication and an addition conversion factor, then inserting it into the Investigator Tape.

The third program took the radar tracking data, read it in and verified the timing code, and then inserted it into the Investigator Tape.

3.4.2 Analysis File Software

3.4.2.1 Real Data

Once the Investigator Tape is created, the next step is to prepare the Analysis files. At this point, the user must decide on the time interval of interest. This information is required in order to execute the software and it should be the same for both sets of operations.

The first step in the process is to download selected data from the Investigator and GPS tapes. This is accomplished by executing DOWN_LOAD_GRAVITY and GPS programs, respectively. It should be noted that an intermediate program is included in the creation of the Navigation Filter input file. This intermediate step makes the units in the Investigator Tape comparable with the GPS format.

The next step is to create a merged data set that can be used by the filter software. This is accomplished by running TCSECT3 to create the file for the Differential GPS Bias Function, or TCSECRF to create the merged file for the Navigation Filter. Although this step could have been eliminated by making these operations a subprocess of the filter software, the run time made this option infeasible.

3.4.2.2 Simulated Data

This software system also allows the user to create simulated balloon data. The simulated data contain ERRORS of known quantities and can be used to validate and fine-tune the filter operations.

Simulated data can be generated by running TCSIM3 or BALNEW. Each program prompts the user for initial values and time parameters. The resulting file is written in the same format as the real data so that either real or simulated data can serve as inputs to the filter.

3.4.3 Differential GPS Bias Software

If the user has previously executed GPS and TCSECT3 to generate a real data file, or TCSIM3 to create a simulated file, then it is possible to obtain bias and noise estimates by using the GROUND program. Unlike the Navigation Filter software, this program runs the duration of the entire file. This feature ensures that bias estimates are available for the time period selected by the Navigation Filter.

See Section 3.5 for more information on the GROUND program.

3.4.4 Navigation Filter Software

The final step in this system is to run the Navigation Filter. The software was written to perform Kalman filtering operations and generate balloon trajectory for any of the following options:

- Real data
- Real data with bias estimates
- Simulated data
- Simulated data with simulated bias estimates.

The user must supply the program a set of parameters that are used in executing the filter operations. A more detailed description of this program is presented in Section 3.5.

3.5 Methods and Procedures

This section provides a more detailed description of the software that comprises this system. For each major function, the inputs, processing, and resulting outputs of each program are presented.

3.5.1 Creation of Investigator Tape

See the APPENDIX which contains AFGL Form 6's on the programs.

3.5.2 Creation of Analysis File

3.5.2.1 CONVERT Program

Input - The data items that are required inputs to this program are contained in the Investigator Tape.

Processing - The VSA data contained in the input file is converted from scientific to engineering units. In addition, any missing values are recoded as 999.

Output - This program generates one output file that contains the same variables and order as the input file.

3.5.2.2 TCSECT3 Program

Input - The program prompts the user for the beginning time and the time length of the segment of GPS data he/she would like to create. It requires the following files in the user's directory: D4110F1.DAT and D4110F2.DAT (ephemeris data for the two ground stations), D4120F1.DAT and D4120F2.DAT (clock data for the two ground stations), D7210F1.DAT and D7210F2.DAT (pseudorange data for the two ground stations) and D7230F1.DAT and D7230F2.DAT (doppler phase data for the two ground stations).

Processing - The program creates a data file to be used as input to the GROUND program. It merges time-tag update, weather, ephemeris, clock, pseudorange, and doppler values in chronological order within the time interval specified by the user.

Output - The merged data file created by TCSECT3 appears under the name TCTST.DAT.

3.5.2.3 TCSIM3 Program

Input - The program prompts the user for an integer indicating whether the errors incorporated into the simulated data should be initialized to zero or set by the user. If to be set by the user, prompts will occur for the following biases: clock offset for two ground stations, frequency offset for two ground stations, and pseudorange biases for four satellites. The program then prompts the user for starting and ending time of the simulated data to be created. If the user indicates that he/she wants to change the latitude and longitude of the ground stations, the program will ask for the new latitudes and longitudes.

Processing - The program uses the initial biases and locations to compute simulated clock, ephemeris, pseudorange and doppler shift values indicative of a circular, non-processing orbit.

Output - The program creates an output file SIMULG.DAT in which the simulated values of clock, ephemeris, pseudorange and doppler shift values are arranged in chronological order according to time tag. The file can be used as input to GROUND if the simulated data option is chosen.

3.5.2.4 GROUND Program

Input - The program prompts the user for an integer indicating whether merged real data or simulated data is being used. It also asks for the time of the first measurement of the input file. If real data is being used, the program will need the input file TCTST.DAT. If simulated data is being used, it will need the file SIMULG.DAT.

Processing - The program uses a Kalman filtering technique to form acceptance and rejection decisions on the pseudorange and doppler data as reported to two ground stations from four satellites.

Output - The program prints on the screen the number of measurements accepted by the filtering routine. Two data files are also created. GROUT.DAT is a user output file containing measurement noises, state vectors, and other statistics associated with each measurement. GRTNAV.DAT is a file containing biases that can be used as input to the navigation file.

3.5.2.5 TCSECRF.FOR Program

Input - Input for this program consists of the output file from CONVERT.FOR (the Balloon IMSP data) and GPS data blocks for the balloon, as follows:

CONVERTED.DAT
D4110F4.DAT
D4120F4.DAT
D3210F4.DAT
D5010F4.DAT
D7210F4.DAT
D7230F4.DAT

Processing - This program merges seven (7) individual data files into one data file named TCROB.DAT Data is sorted by GPS Time with GPS data blocks preceding IMSP data blocks for the same instant in time.

Output - TCROB.DAT

3.5.2.6 BALNEW.FOR Program

Input - Input to this program consists of operator input of an arbitrary starting time and time length of data.

Processing - This program creates simulated data files with pre-selected errors incorporated into the data. This data can be merged in the same manner as the real data and input into the Navigation Filter for processing.

Output - Output consists of seven (7) simulated data files:

S4110F4.DAT
S4120F4.DAT
S7210F4.DAT
S7230F4.DAT
SCONVERTED.DAT
S3210F4.DAT
S5010F4.DAT

3.5.2.7 NAVFIL.FOR Program

Input - Input to program NAVFIL.FOR consists of one data file created by program TCSECRF.FOR: TCROB.DAT.

Processing - The processing involves a Kalman filter algorithm which computes the errors in position of dependent parameters used to determine Balloon-gondola spatial location.

Output - Output consists of updated balloon-gondola position based upon successful incorporation of new position dt into the error vector. The output file is called NAVOUT.DAT.

4. EXAMPLE OF RUN

$RUN TCSECT3

Differential GPS Bias File Merge Program

This program merges the different data files of real or simulated data and puts them all into one file called TCTST.DAT for use in the Kalman filter to obtain bias estimates. The input files include:

D4110F1.DAT,D4110F2.DAT - Ephemeris data files
D4120F1.DAT,D4120F2.DAT - Clock data files
D7210F1.DAT,D7210F2.DAT - Pseudorange data files
D7230F1.DAT,D7230F2.DAT - Doppler data files
D5010F1.DAT,D5010F2.DAT - Weather data files
D3210F1.DAT,D3210F2.DAT - Time tag update data files
F1 denotes station # 1 and F2 denotes station # 2.

For this program, the data files D3210F1,F2 and D5010F1,F2 are small, so the values for the data in these files are already included in this program. (In other words, these files are not read in.) The user only has to input the starting time of the data set he/she wants and the time length. The output file is TCTST.DAT.

Input the beginning time and time length (in seconds)
404926.0,120.0

All input data files are opened. Searching for the requested sections of data.

Found first Pseudorange record in file # 1
Found first Pseudorange record in file # 2
Found first Doppler record in file # 1
Found first Doppler record in file # 2

At the requested part of file.
Processing data ...

```
Reached end-of-file on Pseudorange file #            1
Reached end-of-file on Pseudorange file #            2
Reached end-of-file on Doppler file #          1
Reached end-of-file on Doppler file #          2
Reached end-of-file on Ephemeris file #          1
Reached end-of-file on Ephemeris file #          2
Reached end-of-file on Clock data file #          1
Reached end-of-file on Clock data file #          2
```

```
Program complete, file TCTST.DAT is created for input into the Ground data
Kalman filter.

FORTRAN STOP
```

$RUN TCSIM3

GPS Simulator Program

This program generates a file of simulated GPS data from two ground stations to four satellites. The name of the output file for the simulated data is SIMULG.DAT.

The errors that are to be incorporated into the simulated data are:

a. The clock offset (for each ground station)
b. The frequency offset (for each ground station)
c. The pseudorange error (for each satellite)
d. The doppler error (for each satellite).

Input: 1 - if you want to initialize any of them to new values.
Input: Ø - if you want to keep them equal to zero.

```
1
    Enter the clock offset bias (real) for station 1
1.Øe-4
    Enter the clock offset bias (real) for station 2
1.Øe-4
    Enter the frequency offset bias (real) for station 1
1.Øe-2
    Enter the frequency offset bias (real) for station 2
1.Øe-2
    Enter the pseudorange bias (real) for satellite 1
1.Øe-3
    Enter the pseudorange bias (real) for satellite 2
1.Øe-3
    Enter the pseudorange bias (real) for satellite 3
1.Øe-3
    Enter the pseudorange bias (real) for satellite 4
1.Øe-3
    Enter the starting time for the data (second-real).
4ØØØØØ.Ø
    Enter the ending time for the data (second-real).
4ØØ12Ø.Ø
    The locations of the ground stations have been initialized:

    Station 1:                        Station 2:
                       Latitude
degrees:  32.ØØØØ                     32.ØØØØ
minutes:  16.ØØØØ                     56.ØØØØ
seconds:  43.32ØØ                     59.28ØØ
```

```
                         Longitude
degrees: 253.0000                        256.0000
minutes:  14.0000                     42.0000
seconds:  45.6000                     36.0000

Input: 1 - if you want to initialize any of them to new values.
Input: 0 - if you want to keep them equal to their current values.
```

Processing is completed. The simulated data is in SIMULG.DAT.

FORTRAN STOP

$RUN GROUND

Ground Filter Program

The FORTRAN program GROUND reads in satellite measurements of pseudorange and doppler phase and estimates the errors in the data using a Kalman filtering technique. The data is transmitted from up to four satellites and received by two ground stations.

```
Type 1 if real data is being used.
Type Ø if simulated data is being used.
1
Type in the time of first measurement (floating point).
4Ø4926.Ø
          8 pseudorange measurements accepted
          Ø doppler phase measurements accepted
```

FORTRAN STOP

$RUN TCSECRF

Simulation File Merge Program

This program merges the different data files of BALLOON flight data and puts them all into one file called TCROB.DAT for use in the Kalman filter for the balloon. The input files include:

D4110F4.DAT - Ephemeris data file
D4120F4.DAT - Clock data file
D7210F4.DAT - Pseudorange data file
D7230F4.DAT - Doppler data file
D5010F4.DAT - Weather data file
D3210F4.DAT - Time tag update data file
CONVERTED.DAT - IMSP data file

The user only has to input the starting time of the data set he/she wants and the time length. The output file is TCROB.DAT.

Opened all input data files. Searching for the requested sections of each data file.

Found first pseudorange record
Found first record in Doppler data file
Found first record in IMSP data file

Found requested part of file, processing data ...

Reached end-of-file on pseudorange data file
Reached end-of-file on Doppler data file
Reached end-of-file on Ephemeris data file
Reached end-of-file on clock data file
Reached end-of-file on IMSP data file
Reached end-of-file on time tag update file

Program complete, file TCROB.DAT is created for input into the balloon Kalman filter.

FORTRAN STOP

$RUN BALNEW

Balloon Data Simulation Program

You will be prompted for synthetic time and location of a balloon launch point.

Type in a beginning GPS time (ex. "1.0", or "1200",)
404000.
Type in an ending GPS time (ex. "20", or "3600.")
404010.
Simulating 11.00000 seconds of IMSP and GPS data

Balloon Starting Data
Enter a starting latitude (deg,min,sec)
33,0,0
Enter a starting longitude (deg,min,sec)
-106,0,0
Enter a starting altitude (meters)
29000.

Ground Station Data

Lat/Lon and altitude for Ground Stations 1 and 2 are:

Station 1	32.83000	/ -106.1200	50.00000
Station 2	30.00000	/ -90.00000	30.00000

If you want to change these, type "1", else type "9"
1

*** Calculating IMSP data....Please wait...***
**** GPS DATA SIMULATION ****

The vector of biases has been initialed to zero. If you want to initialize them to a non-zero value, type 1 and you will be prompted for the new values, else type "9".
9

IMSP data is in output file IMSP.DAT
GPS data is in output file SIMULB.DAT

Processing completed

FORTRAN STOP

```
$RUN NAVFIL

     Navigation Error Filter Processing Program

     Answer Y or N questions with uppercase Y or N.
Do you want to process IMSP data? Y or N?
Y
IMSP data is processed every .1 seconds.  Do you want to change this? Y or
N?
Y
Type in the skip rate, N, to process every Nth IMSP record.  N must be an
INTEGER.  Remember...VSA, compass, and RR data occur every 1 second.
10
Do you want to process VSA data?  Y or N?
Y
Type in the VSA data skip rate, N, to process every Nth VSA measurement.  N
must be an INTEGER.
1
Do you want to process Magnetic Compass data?  Y or N?
Y
Type in the Magnetic Compass skip rate, N, to process every Nth magnetic
compass measurement.  N must be an INTEGER.
1
Do you want to process Range Radar (RR) data? Y or N?
N
Do you want to process GPS data? Y or N?
Y
Type in the GPS data skip rate, N, to process every Nth GPS measurement.  N
must, of course, be an INTEGER.
1
Type in the 3 component XYZ vector of the GPS antenna in METERS above the
IMSP platform.  (REAL numbers)
ATX=
0.0
ATY=
0.0
ATZ=
```

15.

Do you want to use the biases from the Bias Filter in the error estimates? Y or N?

N

Type in the starting time (in GPS units) for the first data file (REAL number)

409346.1

Type in the end time (in GPS units) for reading the last data file (REAL number)

409665.1

BALLOON INITIAL POSITION

ENTER STARTING LATITUDE (deg,min,sec)

EXAMPLE: 32,49,49

33,20,0

ENTER STARTING LONGITUDE (deg,min,sec)

EXAMPLE: -106,0,0

-105,0,0

ENTER STARTING ALTITUDE (meters)

EXAMPLE: 29700.0

29824.0

Type in the beginning compass heading in degrees; East=90.00

EXAMPLE: 45.4

31.2

Program NAVCOM executing. Please wait.......

Processing completed.

FORTRAN STOP

END

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DTIC